A Peridynamic Simulation of Hydraulic Fracture Phenomena in Shale Reservoirs

Siavash Nadimi

Ilija Miskovic

STPLab

Department of Mining Engineering

The University of Utah

Contents

Introduction

- **Unconventional reservoirs are essentially any reservoir that requires special recovery operations**
  - ✓ Tight-gas sands,
  - ✓ Oil shales,
  - ✓ Heavy oil sandstones,
  - ✓ Gas shales, and
  - ✓ Coal-bed methane

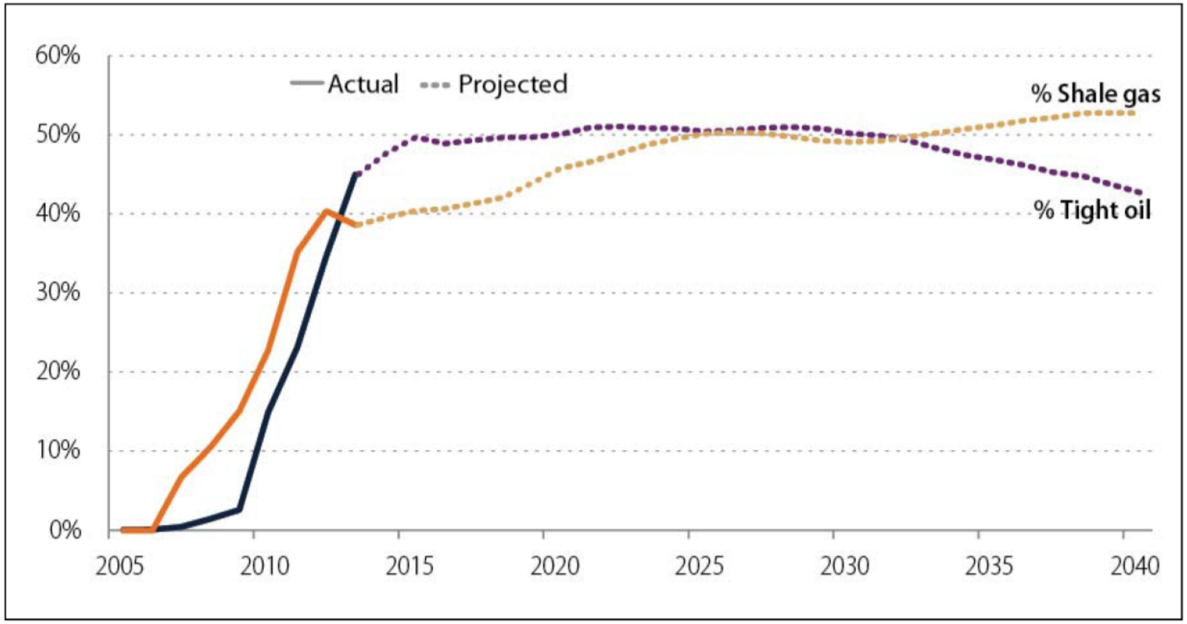
- **HUGE amounts of unconventional resources!**

http://www.slb.com/services/technical_challenges/geomechanics/reservoir_management/unconventional_reservoirs.aspx

Introduction (Cont.)

- **The production of unconventional reservoirs has increased:**
  - ✓ **Directional drilling**
  - ✓ **Hydraulic fracturing**

Percentage of U.S. Oil and Natural Gas from Tight Oil and Shale Gas



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2014*, http://www.eia.gov/oiaf/aeo/tablebrowser/ and other EIA data.

Note: Prior to 2007, the Energy Information Administration did not report tight oil and shale gas data.

Hydraulic Fracturing

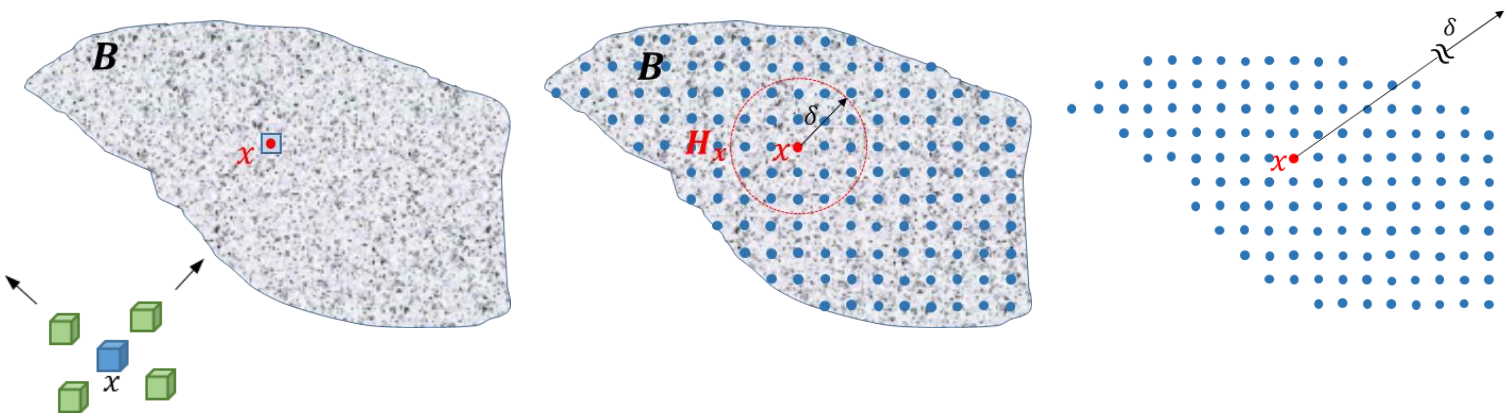
- Successful economical production depends on the existence of effective conductivity
- Hydraulic fracturing is a well stimulation treatment
- It involves the coupling of at least three processes:
  - ✓ The mechanical deformation induced by the fluid pressure on the fracture surfaces;
  - ✓ The flow of fluid within the fracture;
  - ✓ The fracture propagation

Numerical simulations

- Continuum-based Numerical Methods
  - ✓ FEM
  - ✓ XFEM
- Discrete element method (DEM)
  - ✓ BPM
- Numerically simulation of hydraulic fracturing that model the actual process can be very difficult
  - ✓ Size and time of simulation
  - ✓ A suitable mesh on the evolving crack surface
  - ✓ Large-scale slip and opening of fracture elements are not allowed

Peridynamic (PD) Theory

- **PD is a non-local method**
- **PD establishes the connection between classical continuum mechanics and molecular dynamics**

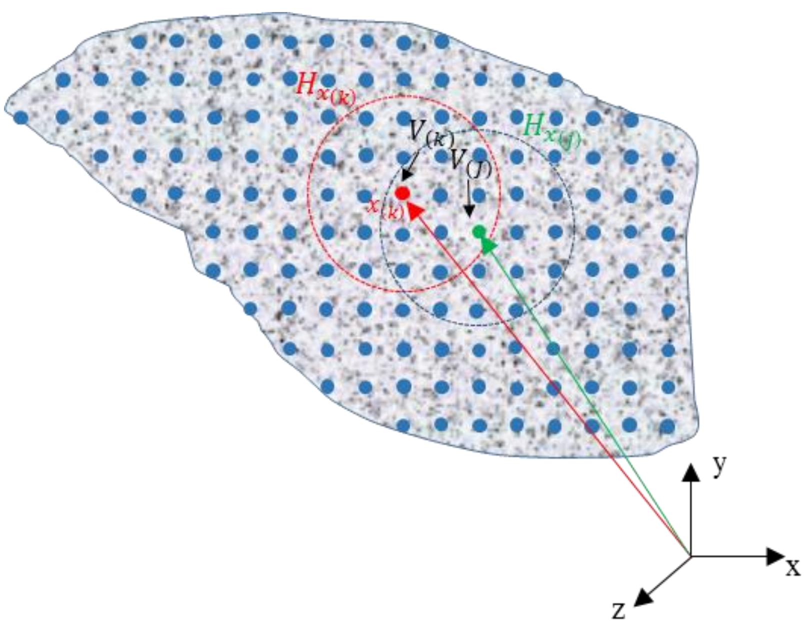


Local **PD** **Molecular dynamics**

- A particle (infinitesimally small free-body) does obey the Newton's second law.

- The physical interaction between two particles is called "bond"

- In the case of the local theory, points of a material are influenced by the point in the vicinity



- Each point interacts with an infinite number of points in a certain distance named “material horizon”, δ
- It is enabled to compute the displacement everywhere whether or not discontinuities present
- If the radius , $\delta,$ becomes infinitely large, the PD theory changes to the molecular dynamics
- If the radius , δ, decreases to the size of the particle dimension, the PD theory will switch to the classical continuum mechanics

- The peridynamic equation of motion at a reference configuration of x and time t is given as:

Response function

Body Force

$$\boxed{\rho}\frac{\partial^2 \boxed{u}}{\partial t^2} = \int_{\boxed{H}} \boxed{dV}_x \, \boxed{f}(u(x',t),u(x,t),x',x,t) + \boxed{b}(x,t)$$

Integration Variable

Density

Neighborhood of x

displacement vector

- PD
  - ✓ Bond-Based
  - ✓ State-Based

- **Simulation**

- Creating Geometry
  - region, create box;
  - read data command
- Applying Models
  - Viscoelastic
- Applying boundary Condition
  - Fixing the lower wall
- Applying HF Pressure
  - Three different injection rate
- Computing Damage
  - Damage per atom
  - Dilatation per atom

PDLAMMPS Simulation

- PDLAMMPS coding

  ✓ Units and Dimension
    3D
    SI units

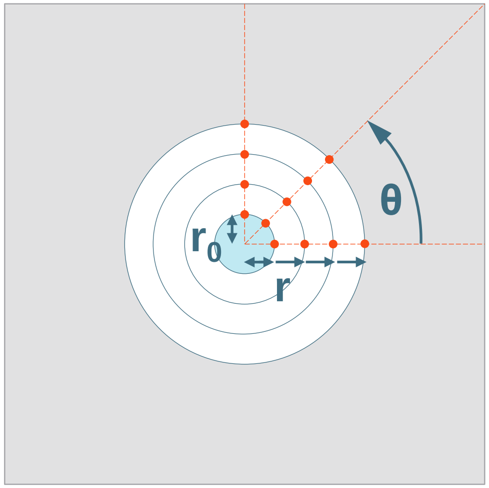
  ✓ Dimensions (mm):
    Simulation domain: 80 mm*80mm*80mm
    Perforation: D=10mm, L=20mm

  ✓ Lattice

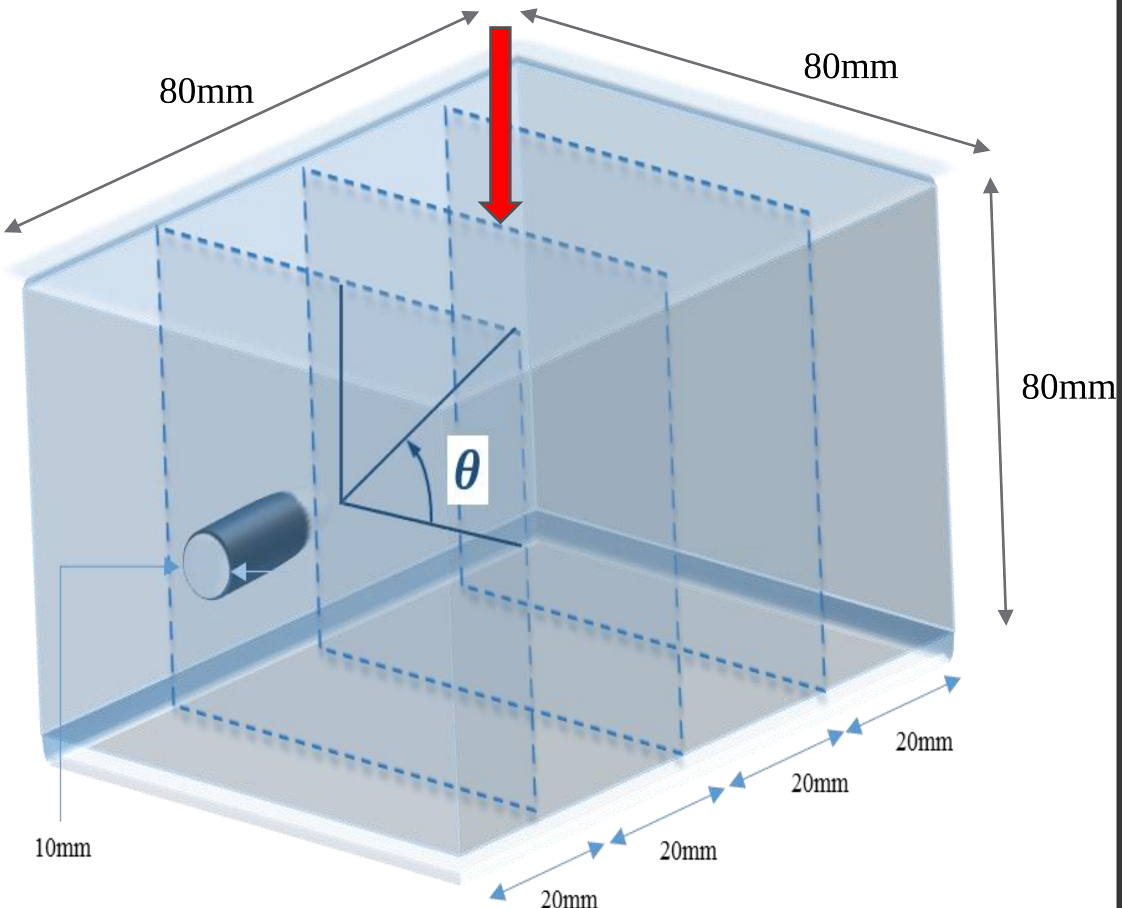
  ✓ Lattice is simply a set of points in space

  ✓ Region

Geometry



$$\left(\frac{r}{r_0} = 1, 2, 3, 4\right)$$

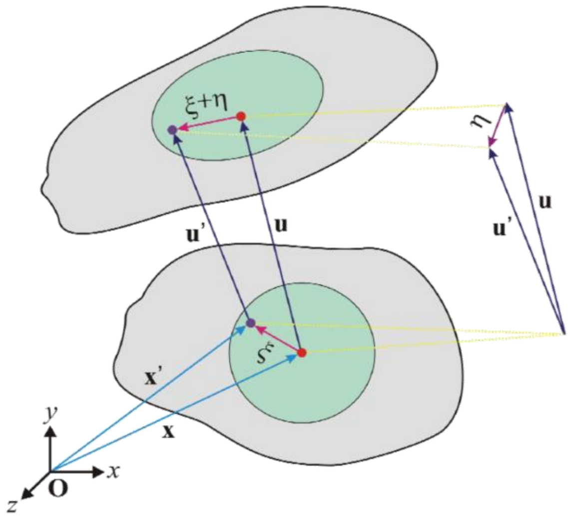


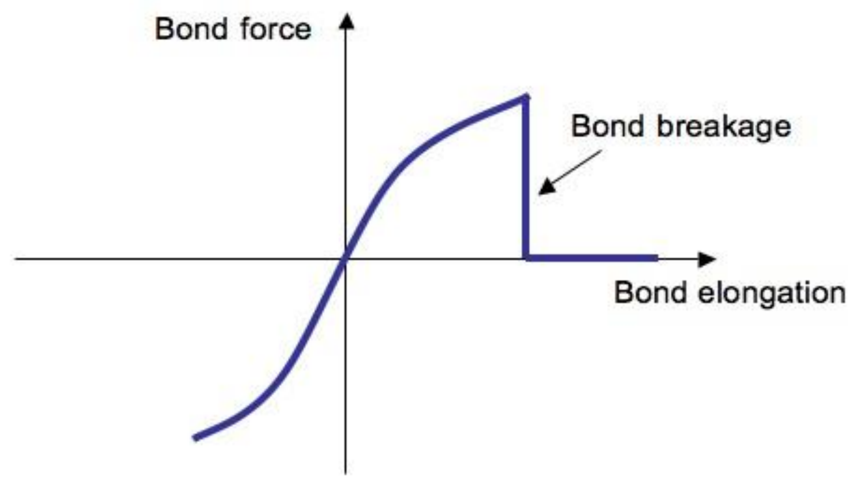
PDLAMMPS Simulation (Cont.)

- Horizon
  - ✓ δ: 2-5 times of Lattice size
- Lattice
  - ✓ 1/3 of δ
  - ✓ The lattice style must be consistent with the dimension of the simulation
- Fixing the lowerwall
- Different injection rates
  - ✓ 2.07, 2.96 and 3.85 bbl/min
- Damage
  - ✓ Damage per atom
  - ✓ Dilatation per atom

Damage

- Damage or fracture is incorporated into the model through the bond when their strain exceed some critical value, S_0
- Once a bond breaks, it does not sustain any force any longer

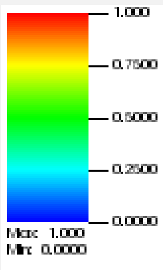
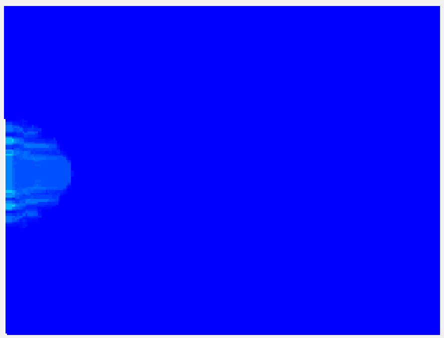
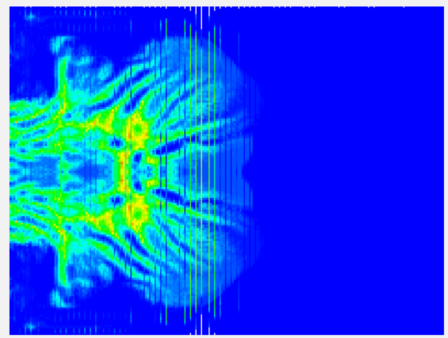
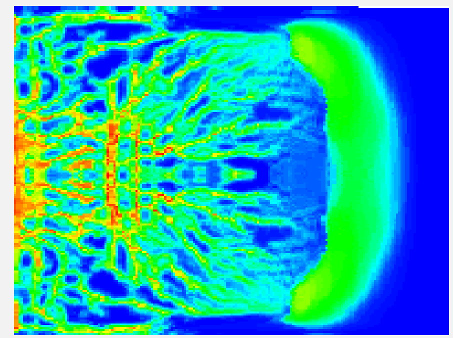
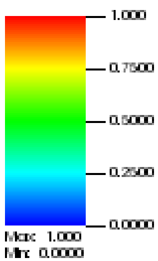
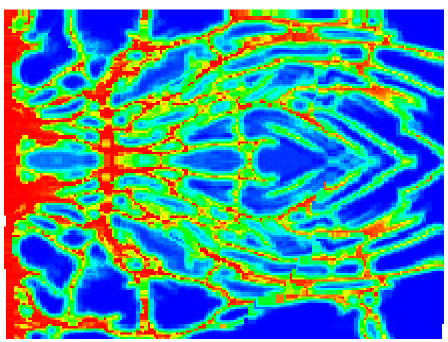
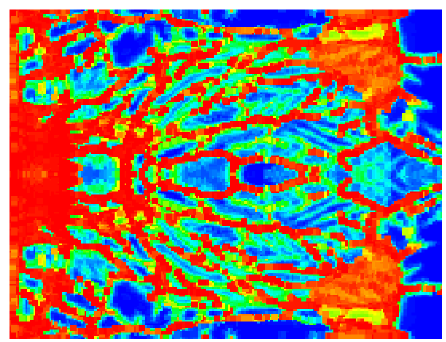
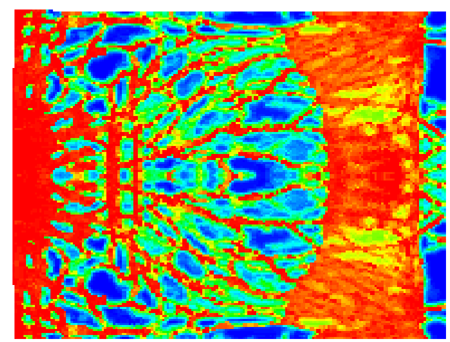




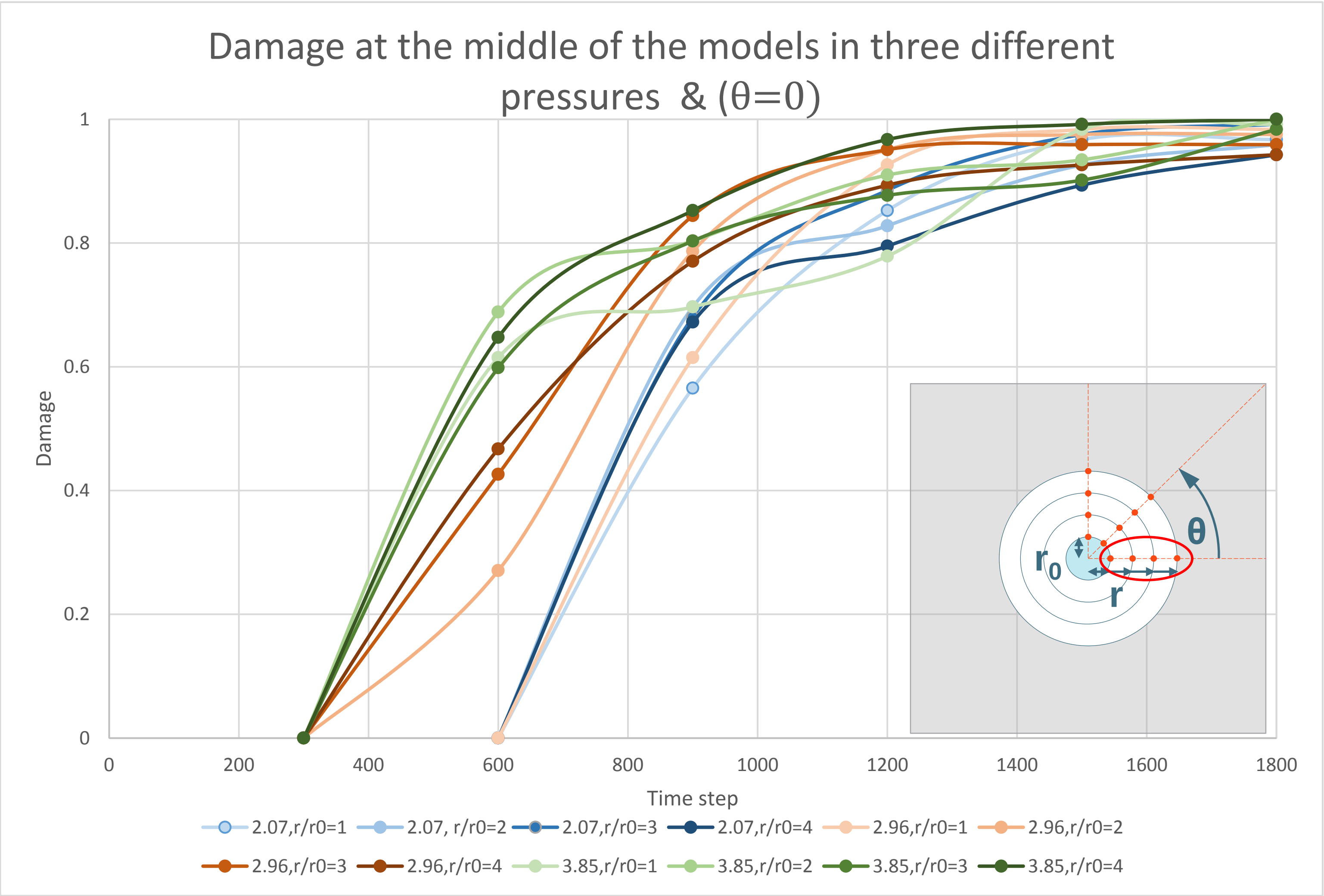
$$S_0(t,\eta,\xi) = S_{00} - \alpha s_{min}(t,\eta,\xi)$$

$$\xi = x - x' \qquad \eta = u' - u$$

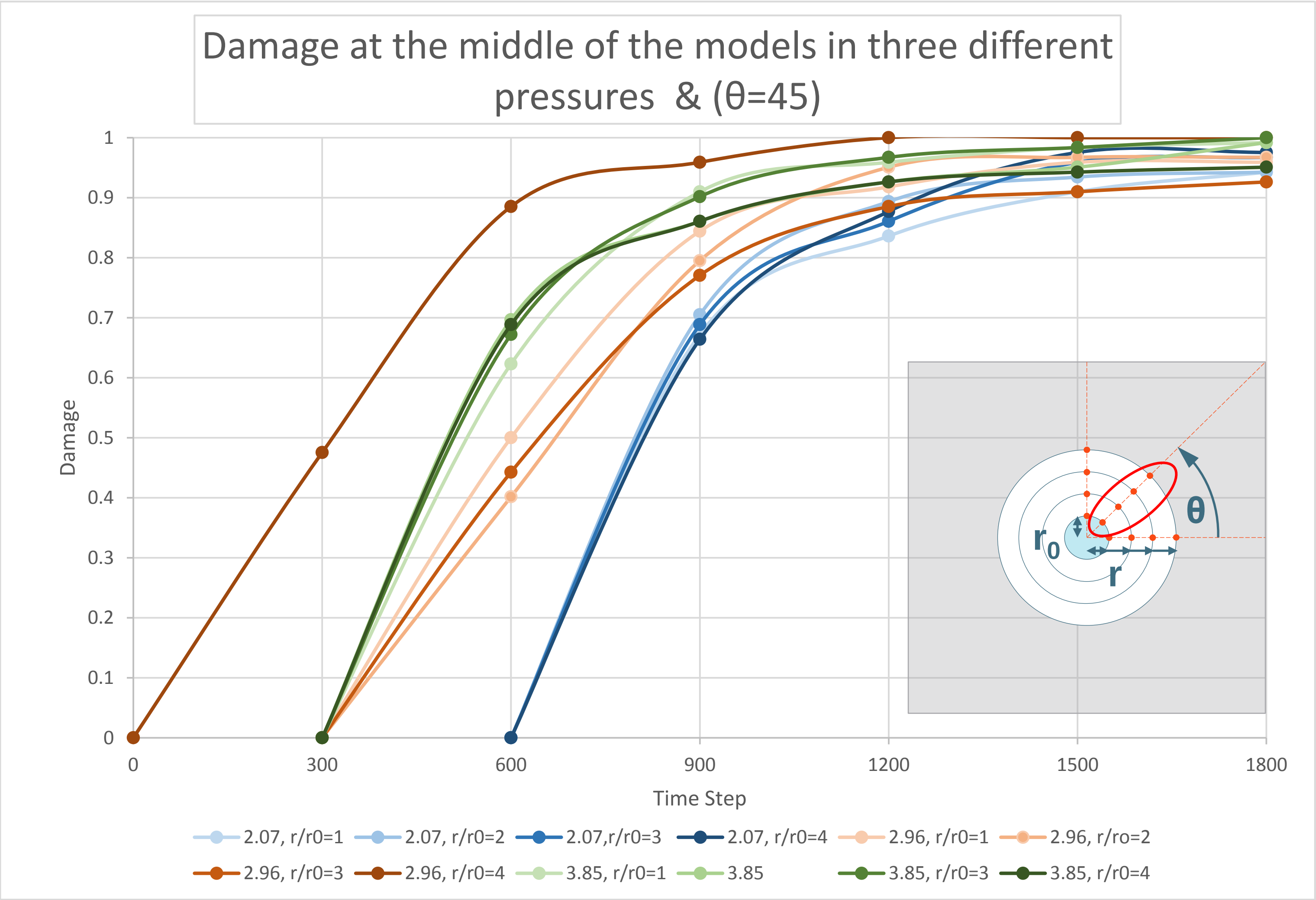
Damage

Time step	2.07 bbl/min	2.96 bbl/min	3.85 bbl/min
600 			
1500 			

Damage

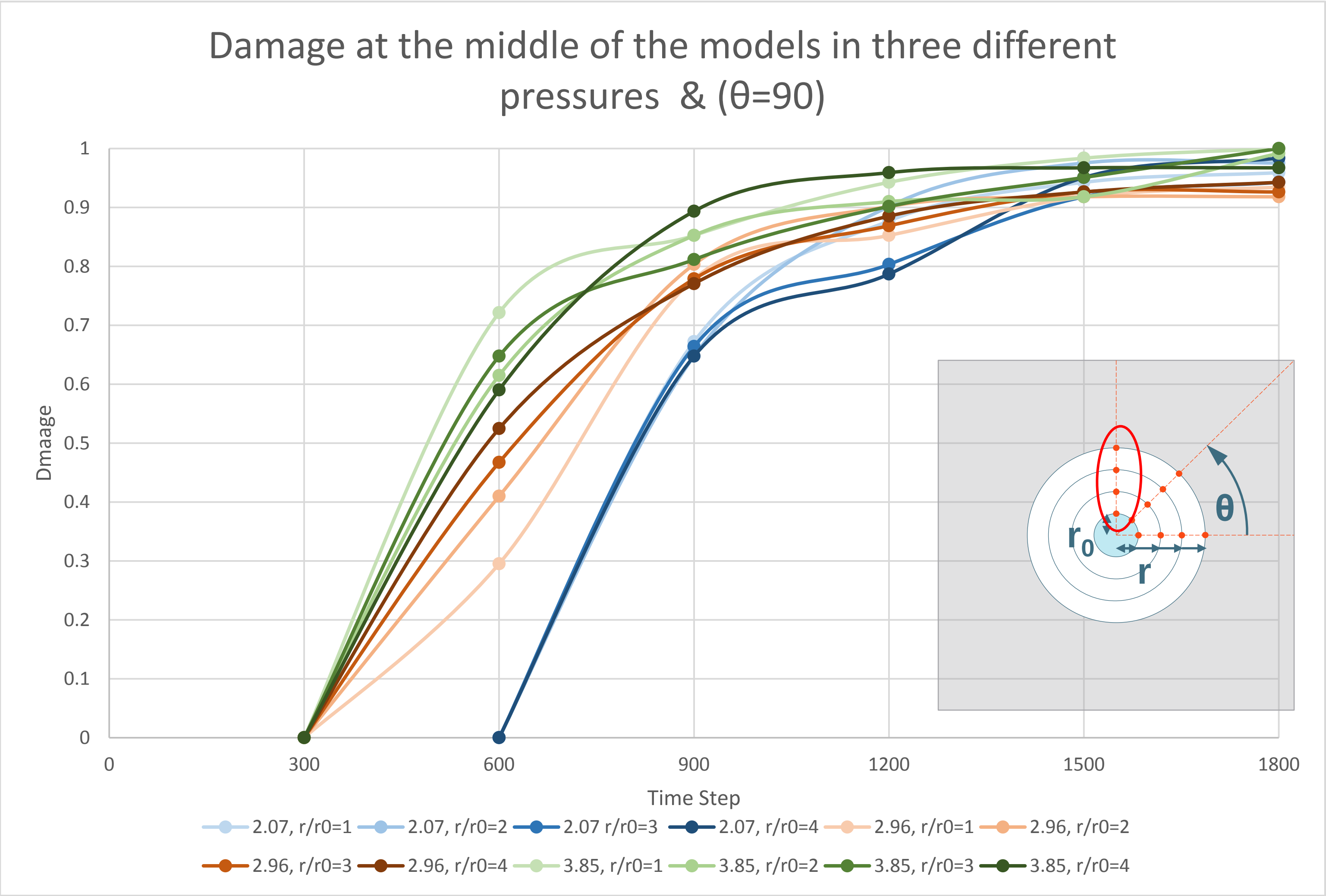

Damage at the middle of the models in three different pressures & (θ=0)
Damage
Time step
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
1200
1400
1600
1800
θ
r0
r
2.07,r/r0=1
2.07, r/r0=2
2.07,r/r0=3
2.07,r/r0=4
2.96,r/r0=1
2.96,r/r0=2
2.96,r/r0=3
2.96,r/r0=4
3.85,r/r0=1
3.85,r/r0=2
3.85,r/r0=3
3.85,r/r0=4

Damage

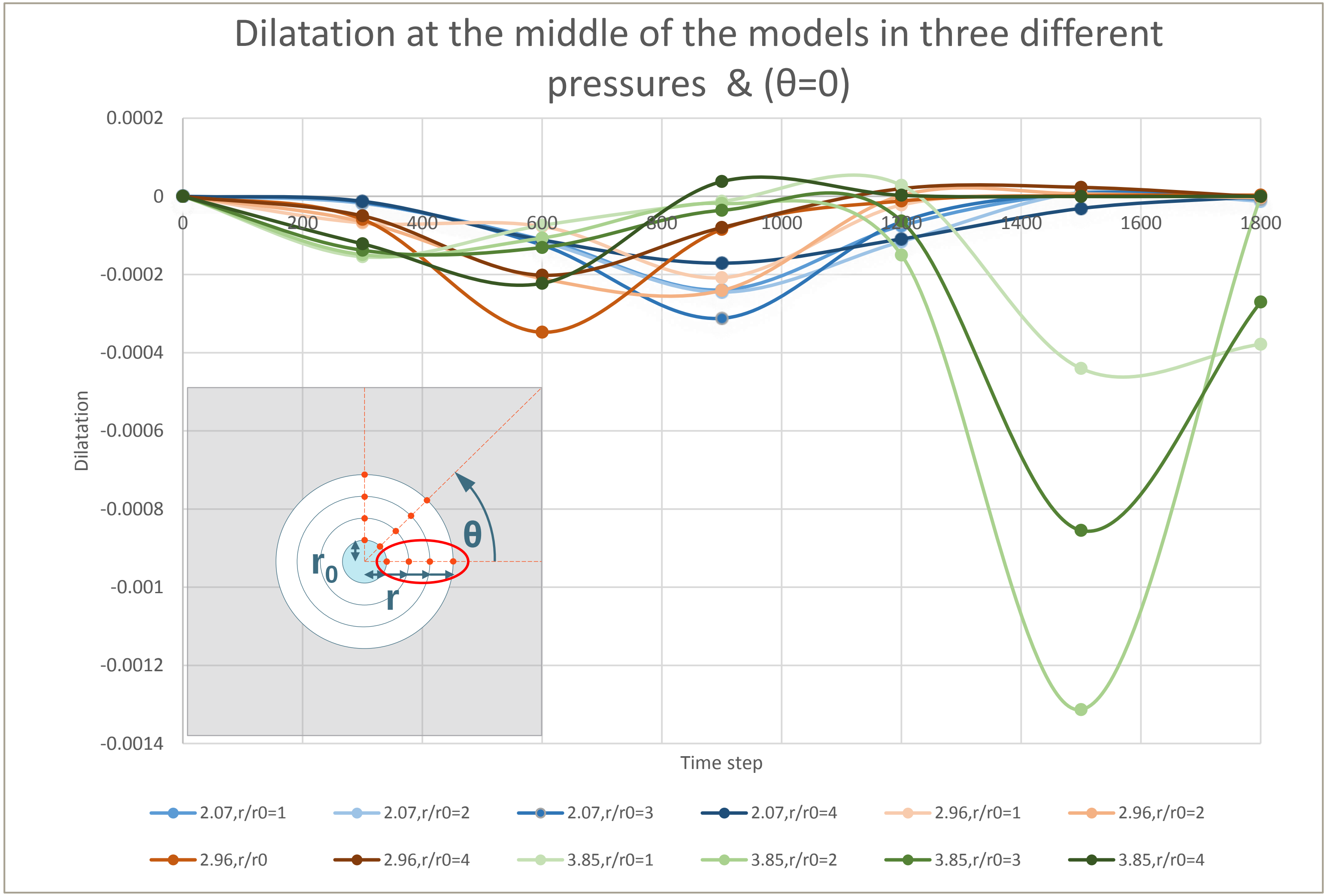


Damage at the middle of the models in three different pressures & (θ=45)
Damage
Time Step
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
300
600
900
1200
1500
1800
r0
r
θ
2.07, r/r0=1
2.07, r/r0=2
2.07,r/r0=3
2.07, r/r0=4
2.96, r/r0=1
2.96, r/ro=2
2.96, r/r0=3
2.96, r/r0=4
3.85, r/r0=1
3.85
3.85, r/r0=3
3.85, r/r0=4

Damage


Damage at the middle of the models in three different pressures & (θ=90)
Dmaage
Time Step
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
300
600
900
1200
1500
1800
2.07, r/r0=1
2.07, r/r0=2
2.07 r/r0=3
2.07 r/r0=4
2.96, r/r0=1
2.96, r/r0=2
2.96, r/r0=3
2.96, r/r0=4
3.85, r/r0=1
3.85, r/r0=2
3.85, r/r0=3
3.85, r/r0=4
r_0
r
θ

Dilatation



Dilatation at the middle of the models in three different pressures & (θ=0)
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
-0.001
-0.0012
-0.0014
Dilatation
0
200
400
600
800
1000
1200
1400
1600
1800
Time step
θ
r0
r
2.07,r/r0=1
2.07,r/r0=2
2.07,r/r0=3
2.07,r/r0=4
2.96,r/r0=1
2.96,r/r0=2
2.96,r/r0
2.96,r/r0=4
3.85,r/r0=1
3.85,r/r0=2
3.85,r/r0=3
3.85,r/r0=4

Conclusion

- High fidelity simulation that can bridge multiple scales for molecular to micro-scales

- Low computed cost

- Easy to integrate with continuum mechanics

- The most important advantage of the peridynamic approach over other methods for fracture modelings is that it does not require any additional formulation that determines when a crack should grow, its velocity, direction, branching and relationship between length and width of the crack.

- The equation of motion deals with all of these phenomena

Questions?